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W.B. Verwey

THE DEVELOPMENT OF HIGHLY PRACTICED
SKILLS: A STARTING POINT FOR DRIVER
MODELLING

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Title: The development of highly practiced skills: a
                   starting point for driver modelling

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                   Group: Traffic Behavior

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SUMMARY

This report argues that in order to develop reliable intelligent
interfaces in motor cars, a driver model should be developed which
reflects human information processing mechanisms and, more specifical-
ly, mechanisms of skill acquisition. Two mechanisms are proposed to
underlie skill acquisition, namely involuntary priming and voluntary
preparation. On this basis three alternative models of skill acquisi-
tion are proposed that differ with respect to the effects of voluntary
control at the perceptual and response level of information process-
ing. Subjects carried out two-choice reactions in rapid succession.
The most important experimental manipulations were (1) whether the
first choice reaction predicted the second and (2) the degree of
transfer of training to conditions where predictivity changed. In
addition, stimulus presentation was for some subjects always visual
whereas for other subjects only the first stimulus was visual and the
second was auditory. The results support a model asserting that
involuntary effects of priming evolve only at the perceptual level but
not at the response level. In addition, they support earlier findings
that preparation for the second reaction occurs, in part, before
execution of the first one. Correlational analyses of individual
differences indicate that an overlapping strategy during training
yields involuntary priming whereas a sequential strategy without
overlapping preparation does not. Together, the results are in close
agreement with a connectionist-control model of human information
processing which consists of separate processing modules each of which
can be described as a neural network (Schneider & Detweiler, 1987,
1988). Finally, implications for the Generic Intelligent Driver
Support (GIDS) system are presented.

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De ontwikkeling van goed getrainde vaardigheden: een beginpunt voor
bestuurdermodellering

W.B. Verwey

SAMENVATTING

In dit rapport wordt betoogd dat voor de ontwikkeling van betrouwbare
intelligente interfaces in de auto, een model van de bestuurder moet
worden ontwikkeld dat gebaseerd is op inzicht in menselijke informa-
tieverwerkingsmechanismen en, meer specifiek, inzicht in de wijze
waarop taakvaardigheden verworven worden. Er wordt beargumenteerd dat
verwerving van taakvaardigheden is gebaseerd op twee mechanismen,
onvrijwillige priming en vrijwillige preparatie. Op grond hiervan
worden drie modellen voor de verwerving van taakvaardigheden voorge-
steld welke verschillen met betrekking tot de effecten van vrijwillige
sturing op het waarnemings- en responsniveau van de informatieverwer-
king. Proefpersonen voerden twee twee-keuze reactietijd taken snel na
elkaar uit. De belangrijkste experimentele manipulaties waren (1) of
de eerste keuzetaak de tweede voorspelde en (2) de mate waarin het
geleerde overgedragen werd naar condities waarin de voorspellende
waarde was veranderd. Daarnaast werden de stimuli aan sommige proef-
personen altijd visueel aangeboden terwijl andere proefpersonen de
eerste stimulus visueel en de tweede auditief aangeboden kregen. De
resultaten ondersteunen een model dat er vanuit gaat dat onvrijwillige
effecten van priming alleen op het perceptuele niveau ontstaan en niet
op het responsniveau. Ook worden eerdere bevindingen ondersteund dat
preparatie voor de tweede keuzetaak gedeeltelijk uitgevoerd wordt nog
voordat de eerste reactie gegeven is. Een correlatie-analyse van
individuele verschillen geeft aan dat een overlappende preparatie-
strategie leidt tot onvrijwillige priming effecten op het perceptuele
niveau terwijl een puur sequentiële strategie zonder overlappend
preparatie dat niet doet. Deze resultaten komen goed overeen met een
connectionistisch model van informatieverwerking dat gebaseerd is op
gescheiden verwerkingseenheden die elk beschreven kunnen worden als
neurale netwerken (Schneider & Detweiler, 1987, 1988). Tenslotte
worden de implicaties beschreven voor het Generic Intelligent Driver
Support (GIDS) systeem.

1 INTRODUCTION

1.1 An overview of GIDS

The overall objective of the GIDS project (DRIVE V1041) is to determine requirements and design standards for a class of Generic Intelligent Driver Support (GIDS) systems that conforms with the information requirements and performance capabilities of the individual driver. The project will provide recommendations for such systems and an operational prototype will be developed in order to demonstrate some of the essential features of the GIDS concept.

Gids systems are designed to accept information from sensors and dedicated driver support applications, and to filter, integrate, and present this information in ways which are consistent with the intentions and capabilities of individual drivers. The GIDS approach will provide recommendations to a broad spectrum of users, including manufacturers of dedicated driver support systems and road traffic authorities.

The use of high-technology in vehicles will increase the potential amount of information presented to drivers and the number of tasks they will have to carry out. Even with current technology drivers can use in addition to driving a navigation system, control and talk on an in-car telephone, adjust the on-board cruise-control and control the stereo and climate system. With increasing technological possibilities the design of on-board devices will have to be more and more determined by human capabilities instead of the technical feasibility.

One major point of concern is that the driver will be overloaded by information from these electronic devices. Therefore, within the GIDS project a Dialogue Controller is in development which should prevent the driver from being overloaded (Verwey, 1990a,c). Basically, the Dialogue Controller operates by presenting information at times that the driver is not attending more important tasks. In order to determine what the driver is currently doing and what the driver will be doing shortly afterwards, a detailed processing model of the driver has to be developed which goes beyond plain stimulus-response models (Michon, 1987). This incorporates the possibility to estimate on-line driver workload. Another approach to solve the problem of driver overload is to design interfaces so that the driver can easily learn the properties of the interface and not much attention is required to control the interface (Verwey, 1990a). Again, proper modelling or, at least, insight in the basic mechanisms involved in acquiring complex

skills is needed. So, the need for a proper model of information processing in the human driver is required for two alternatives to tackle the driver overload problem, on-line prediction of driver actions enabling *estimation of current driver workload* and off-line prediction of driver-car interaction with alternative interfaces.

One major problem with modelling the human operator, is that "Most models are normative and do not adequately represent individual differences or the sources of error in operator performance" (McMillan, 1989, p.471). In other words, the models that are available at the moment do not encompass the great variety of human functioning (see McMillan et al., 1989, for a state-of-the-art on current model-ling *in system design). This paper attempts to support* the quest for a detailed theory on human skill acquisition required for building a comprehensive model *of driver performance* by investigating, in detail, the mechanisms underlying skill acquisition.

1.2   Theoretical considerations

A well-known phenomenon in human skill acquisition is that tasks in a consistent task environment require less attention with practice as compared to tasks carried out in an inconsistent environment (e.g., Fisk, Skedsvoldy & Oransky, 1988; Verwey, 1990a,c). According to various investigators attentional demands of consistent tasks are reduced since, with practice, fixed behavioral patterns evolve which do not require much attention (e.g., Carr, 1979, 1984; Miller, Galanter & Pribram, 1960; Neumann, 1987). Although evidence for the existence of fixed behavioral patterns has been found in various task domains among which the driving task (e.g., Brown, 1962; Duncan, Williams & Brown, in press; Hale, Quist & Stoop, 1988; Van der Horst, 1990) not much researchers have investigated the possibility to describe the driving task and the resulting workload from this point of view. In line with earlier work (Verwey, 1990b), the present study *proposes two mechanisms* underlying changes in the way information is processed as a result of practice labelled *preparation* and *priming.* Preparation is assumed *to consist of voluntary and attention demanding* advance tuning of the information processing system. Priming is assumed to be a stimulus-driven bias beyond immediate control and not requiring attention.

Three alternative models can be proposed for a situation in which sequential reactions are carried out. The *voluntary control model asserts that,* following practice, the information processing system,

including the response system, is stimulus-driven only after advance
setting of the system by voluntary preparation. Without proper prepa-
ration responses are not activated by any stimulation. This view is
supported by findings that response inhibition occurs only when an
incorrect response is primed that belongs to a small, expected set of
responses (Cohen, Dunbar & McClelland, 1990; La Heij, 1988). Thus, if
a potential response is incorrectly primed the correct response is
delayed because the primed response requires attention demanding
suppression (Buckolz, Deacon & Hall, 1984; Lupker & Katz, 1981). The
major consequence of this view is that action control remains volun-
tarily and attention demanding by prior preparation, whatever the
level of practice.

In contrast, the *involuntary control model* states that when a sequen-
tial reaction pattern has been trained in a consistent environment
involuntary effects of training develop. This view is consistent with
the coactivation strengthening hypothesis (Hebb, 1949; Schneider &
Fisk, 1984) which assumes that, with practice, associations are
strengthened between frequently coactivated nodes in a memory network.
These associations cause involuntary effects of prior information
processing by guiding the spread of activation (MacKay, 1982). So,
with practice, priming of response elements in a sequence develops
simply by executing earlier elements. According to some definitions,
this behavior is called automatic (e.g., Stelmach & Hughes, 1983, but
see Neumann, 1984). Support for this model comes from findings that
interresponse times in a response sequence gradually decrease (Brown &
Carr, 1989), that consistent movement patterns can be learned and
carried out without awareness (Cohen, Ivry & Keele, 1990; Nissen,
Knopman & Schacter, 1987) and that fixed movement patterns develop
without an explicit need (Schwartz, 1982). The major characteristic of
this model is that with extensive practice, action control is beyond
voluntary control.

The *hybrid control model* combines elements of the two earlier models.
It states that priming at the perceptual levels of information proces-
sing occurs without intention and does not require attention whereas
priming at the motor level is only possible after attentional prepara-
tion of a response set (Schneider & Fisk, 1984; Taylor, 1977; Verwey,
1990b). This model is consistent with the notion that response-evoca-
tion aspects of a task remain attention demanding with practice
whereas processes at the earlier levels of information processing
(e.g., stimulus identification and categorization) occur without
attention and do not require an explicit intention (Sanders, 1990;
Schmidt, 1983). A commonly accepted notion is that information proces-

sing occurs in separable processing resources (e.g., Allport, 1982; Logan, 1985; McLeod, 1977; Wickens, 1984) or processing modules (Cohen, Dunbar & McClelland, 1990; Schneider, 1985; Schneider & Detweiler, 1987). Since, it has been assumed earlier that priming results from concurrent activation of memory nodes, it follows that priming is only possible between nodes in one processing module. For example, visual stimuli may develop other visual stimuli, and auditory stimuli may prime other auditory stimuli. However, at the perceptual level visual stimuli cannot prime auditory stimuli or vice versa. So, perceptual priming will only occur when successively presented stimuli are in the same sensory modality. However, since priming might also occur at a more central and modality independent level (Bajo & Canas, 1989; Collins & Loftus, 1975) some, and probably less, priming may also occur when successive stimuli are in different modalities.

The aim of this paper is to test deductions of the three alternative models. In the experiment subjects practiced two successive two-choice reactions (cf. Verwey, 1990b). In the training phase of a Predictive-Unpredictive (P-U) condition the first stimulus and response (S_1-R_1) always Predicted the second ones (S_2-R_2). In a first control condition, another group of subjects practiced two independent reactions. Since S_1 did not predict S_2 it was called the Unpredictive condition (U-U condition). In a second control condition a third group of subjects practiced a Memory task (M-U condition) which had no resemblance to the choice reactions. The U-U condition was meant to establish a base-line level of performance when S_1-R_1 did not predict S_2-R_2. The M-U condition was to control for a-specific effects like fatigue and familiarization with the experimental situation (Postman, 1971). Following practice, all subjects assigned to P-U, U-U, and M-U were transferred to the Unpredictive condition. To ascertain that when going from the predictive to the unpredictive condition, performance effects would be due to the nature of changes in the condition and not from a change per se (i.e. a task-aspecific effect), a fourth group of subjects practiced the unpredictive condition and was, then, transfer-red to the predictive condition (U-P). The last condition also offered the opportunity to assess effects of training in the unpredictive condition on performance in the predictive condition. Hence, in P-U a predictive relation was trained which could not be used in the trans-fer phase, and might even disturb performance, whereas in the transfer phase of U-P the predictive relation had to be learned from scratch. Apart from the memory task in M-U, all training conditions had the same choice reactions. The main variable was the extent S_1-R_1 predicted S_2-R_2.

In order to establish the importance of priming at the perceptual level half the subjects in all conditions received S_1 and S_2 in the Visual modality (VV condition) while the other half received a Visual S_1 followed by an Auditory S_2 (VA condition). In total, this yielded eight between-subject conditions as shown in Table I.

Table I Overview of the eight between-subject conditions.

condition modality	training phase	transfer phase	S_2
P-U/VV	S_1-R_1 predictive	S_1-R_1 unpredictive	visual
P-U/VA	S_1-R_1 predictive	S_1-R_1 unpredictive	auditory
U-U/VV	S_1-R_1 unpredictive	S_1-R_1 unpredictive	visual
U-U/VA	S_1-R_1 unpredictive	S_1-R_1 unpredictive	auditory
M-U/VV	memory task	S_1-R_1 unpredictive	visual
M-U/VA	memory task	S_1-R_1 unpredictive	auditory
U-P/VV	S_1-R_1 unpredictive	S_1-R_1 predictive	visual
U-P/VA	S_1-R_1 unpredictive	S_1-R_1 predictive	auditory

The *voluntary control model* assumes that the duration of S_2-R_2 mainly depends on attentive preparation, which is always required irrespective of the level of practice. Consequently, there should be no involuntary effects of prior training since priming of S_2-R_2 processing by S_1-R_1 is not expected. So, RT in the transfer phase will fully depend on P or U, irrespective of prior training; RT_1 and RT_2 in the transfer phase of P-U will be similar to that of U-U and at the level of U-U and U-P in the last blocks of trials of the training phase. Likewise, RT_1 and RT_2 in the transfer phase of U-P will be similar to that of P-U in training. In short, prior training is not expected to affect performance in the transfer phase, other than some decline of RT_2 at a brief response-stimulus interval (RSI) where preparation does not occur during RT_1 (as found by Verwey, 1990b).

In contrast, the *involuntary control model* assumes that, following practice, intentional preparation is no longer required since S_2-R_2 processing is primed by S_1-R_1. Attention demanding preparation of S_2-R_2 during RT_1 (Verwey, 1990b) will gradually disappear, consequently RT_1 will improve more in the training phase of P-U than in that phase of U-U and U-P. In the transfer phase of P-U previously practiced S_1-R_1 S_2-R_2 pairs (consistent trials) prime the "correct" R_2. At the alternative S_1-R_1 S_2-R_2 pair (i.e., the inconsistent trials) the "incorrect" R_2 alternative is primed so that suppression of R_2 is required (Buckolz, Deacon & Hall, 1984; Lupker & Katz, 1981). Suppression may occur

either during RT_1, during RSI, or following presentation of S_2. Response suppression *during* RT_1 will slow RT_1 but will not affect RT_2 as compared to the training phase. Response suppression during RSI or after presentation of S_2 will not affect RT_1. If suppression takes place *during RSI*, RT_2 will only be delayed at brief but not at longer RSIs. If suppression of R_2 occurs *after* presentation of S_2, then a delay of R_2 will occur at inconsistent trials. Only in this last case consistent RT_2s will differ from inconsistent RT_2s.

Finally, the *hybrid control model* assumes involuntary perceptual *priming* and voluntary response preparation. Like the voluntary control model, it predicts no effects of suppression after prior training on RT since responses are not primed and invalid perceptual priming does not disturb processing (Verwey, 1990b). Yet, perceptual priming will affect consistent versus inconsistent trials during the transfer phase of P-U because primed stimuli are processed faster than unprimed stimuli. When priming develops at a *modality dependent level* of information processing, performance on RT_1 in P-U/VV should improve more than in P-U/VA. When priming occurs at a later level, which does not depend on the modality of stimulation, no difference is expected between P-U/VV and P-U/VA.

2   METHOD

2.1   Tasks

In a trial subjects carried out two successive choice reactions. The first reaction was always to a visual stimulus (S_1: the letter 'O' or 'X'). Responses consisted of moving a rocket key up (for 'O') or down ('X') with the left thumb and index finger (R_1). The second stimulus (S_2) consisted either of one out of two tones, differing in pitch (575 vs 1385 Hz) or of two additional visual stimuli ('&' or '$'). In response to these stimuli a key was pressed with the right index finger when S_2 was a 1385 Hz tone or a '&', or with the middle finger when S_2 was a 575 Hz tone or a '$'. R_1 and the onset of S_2 were separated by an interval (RSI) with a variable and unpredictive duration (100, 200, 400, 800, or 1200 ms). RSI always started at R_1 onset.

Sixty-four subjects were randomly divided into eight groups of eight subjects, each assigned to eight different conditions. Four groups received an auditory S_2 and the other four groups a visual S_2. In all conditions, subjects had a training and a transfer phase. There were

four different transfer conditions, each of which had a VV and a VA
group. In the training phase of the Predictive condition S_1-R_1 always
correctly predicted S_2 whereas in the transfer phase S_1 was Unpredic-
tive (P-U/VA and P-U/VV). In the training phase of two control condi-
tions S_1-R_1 never predicted S_2-R_2. In the U-U conditions (U-U/VA and U-
U/VV) the relation remained unpredictive in the transfer phase whereas
it became predictive in the U-P conditions (U-P/VA and U-P/VV). Last-
ly, the training phase of the final control conditions consisted of a
Memory search task (mode M-U/VA and M-U/VV). Stimuli in the memory
task consisted of the digits 1 to 9 and responses were required with
the left thumb to a 3 and a 6 and with the right thumb to all other
digits. The number of trials and the duration of an experimental block
were equal to those in the experimental conditions.

2.2   Apparatus

An S-R interface with external clocks connected to an IBM AT-3 with
video digitizer (Matrox inc.) controlled the timing of events, gener-
ated the visual and auditory stimuli and recorded reaction times. The
visual stimuli were presented on a 35 x 23 cm TV monitor (Barco, CDCT
2/51) 150 cm in front of the subjects. Each visual stimulus had a
visual angle of about 0.8°. In the VV conditions two visual stimuli
were presented in succession, the second stimulus appeared 1.1° below
the first one so that both stimuli fell within a region of 1.9° diame-
ter. Auditory stimuli were presented through a single speaker system.
Reaction time, defined as the time between stimulus onset and moment
of key activation, was measured in milliseconds (ms) for both
responses.

Subjects were seated in a sound-attenuated, dimly-lit 2 x 2 x 2 m
cubicle (Amplisent) in front of a table on which a 17° tilted response
panel was positioned. The panel contained three response keys, one
rocket switch on the left and two push-buttons on the right. The two
push-buttons were mounted 3.2 cm apart and the centers of the two
push-buttons and the rocket key were 12 cm apart.

2.3   Procedure

All subjects performed 18 blocks of trials. Four blocks consisted of
twenty single trials (S_1-R_1 only) and fourteen blocks had 100 dual
trials (except for the M-U condition where the first ten "dual blocks"
consisted of the memory task). The single trial blocks were block 1,

6, 11, and 16. The training phase consisted of the first ten dual blocks (i.e. block 2-5, 7-10, 12, 13). The transfer phase consisted of the last four dual blocks (block 14, 15, 17, 18). Block numbers will be referred to with their dual block number (1 to 14).

Two subjects ran two dual blocks in alternation for seven times, four of which were preceded by a single block. All blocks started with four warming up trials which were discarded from analysis. One dual block took about eight minutes. The full experiment took about four hours per subject. Subjects were informed about errors immediately following each response pair (or each single response in the single and memory conditions). Trials with either response incorrect were discarded from analysis.

2.4   Design and analysis

Both the training and the transfer phase had four independent variables, two of which were varied between and two within subjects. Between subject variables were mode of training/transfer (four levels: P-U, U-U, M-U, U-P) and S_2 modality (two levels: VA and VV). Within-subjects variables were blocks (training phase: 10 blocks, transfer phase: 4 blocks) and RSI (five levels: 100, 200, 400, 800, and 1200 ms).

All blocks had 50 trials with an 'X' and 50 with 'O' as S_1. Again, 50 trials had a 575 Hz tone (in VA) or a '$' (in VV) as S_2 and 50 a 1385 Hz tone or a '&'. Combinations of S_1 and S_2 defined the predictive conditions between S_1 and S_2. One half of the subjects in the training condition of P-U or in the transfer condition of U-i learned that an 'X' fully predicted a 575 Hz tone or a '$', and an 'O' a 1385 Hz tone or a '&'. For the other half of the subjects the relation was reversed. Finally, in the transfer phase of P-U there were two within-subject correspondence levels. Consistent trials were defined as the S-R pair as practiced in the training phase and inconsistent trials as the alternative S-R pair.

Basically, reaction times and error percentages were analyzed in a 4 x 2 x 8 x 14 x 5 (training/transfer mode x S_2 modality x subjects x blocks x RSI) hierarchical design with training/transfer mode and S_2 modality nested under subjects. Separate analyses were carried out on the first ten blocks, which constituted the training blocks (the M-U condition was left out, of course) and the last four (transfer) blocks.

Transfer effects were also analyzed by only taking block 10 and 11 into account, that is, the last block of the training phase and the first block of the transfer phase.

Finally, in the P-U conditions the effects of consistent versus inconsistent trials were assessed in a $2 \times 2 \times 8 \times 4 \times 5$ (consistency x S_2 modality x subjects x blocks x RSI) design with S_2 modality nested under subjects.

2.5   Subjects

Sixty-four students served as subjects. They all received Dfl. 45 for participation and were randomly divided into eight groups of eight subjects each.

3   RESULTS

All RT data were analyzed by univariate mixed-factorial analyses of variance (ANOVAs). Mode of training/transfer (P-U, U-U, M-U, and U-P) and S_2 modality (VV and VA) were between-subject variables, and blocks and RSI were within-subject variables. For R_2 a distinction was made between errors, which were incorrect but not premature responses, and anticipatory responses, which were premature (RT_2 less than 100 ms) and either incorrect or correct. Errors and anticipatory responses were analyzed with an ANOVA on arcsine square root transforms.

First, results will be presented on RT_1 and RT_2 in training and transfer including the effects on RT_2 of consistency in the transfer phase. Next, the effects of S_2 modality on RT_1 and RT_2 will be given in a separate section and, finally, the results of some additional correlation analyses will be presented.

3.1   Practice and transfer effects

Effects on RT_1. Fig. 1 shows mean RT_1 as a function of practice and condition. RT_1 in the *practice phase* was analyzed for the modes P-U, U-U, and U-P. Subsequent analyses addressed the effect of dual versus single RT_1 and the effect of dual training on single performance. Apart from a main effect of blocks ($F(9,378)=50.8$, $p<0.01$), the ANOVA showed an intera. ·ion between the effects of training/transfer mode and

blocks ($F_{(18,378)}=2.13$, $p<0.01$). Pair-wise comparisons showed signifi-
cant differences between the effects of training/transfer mode with
training in ANOVAs on P-U and U-P ($F_{(9,252)}=3.15$, $p<0.01$), on U-U and
U-P ($F_{(9,252)}=2.65$, $p<0.01$) but not in the ANOVA on P-U and U-U ($F<1$).

The ANOVA on single RT_1 in single blocks 1 to 4 showed no effect of the
dual mode in which subjects were training ($F_{(3,56)}=1.53$, $p>0.10$).
Analysis of the difference between single and dual RT_1 performance in
the training phase (on the single blocks and the dual blocks immedi-
ately following a single block), showed that single RT_1 was always
faster than dual RT_1 ($F_{(1,42)}=128$, $p<0.01$) and confirmed that mode of
training did not affect single RT_1. A significant interaction between
mode of training and single/dual was found ($F_{(2,42)}=6.67$, $p<0.01$)
which merely confirmed the effect of predictability on dual RT_1. The
interaction between the effects of single/dual and blocks ($F_{(2,84)}=$
12.4, $p<0.01$) indicated that performance in the dual conditions im-
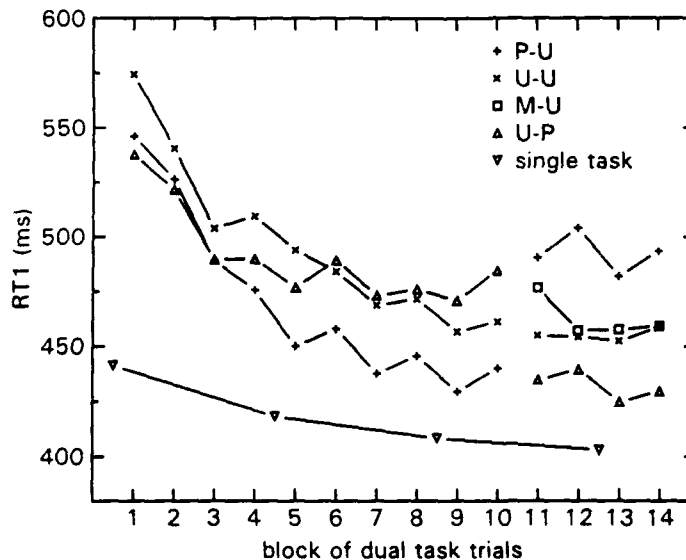proved more than in the single conditions.

Fig. 1 RT_1 as a function of practice and mode of train-
ing and transfer. The first letter indicates predictiv-
ity in the training phase (block 1 to 10), the second
letter indicates predictivity in the transfer phase
(block 11 to 14). P stands for Predictive, U for Unpre-
dictive, and M stands for Memory task.

The analysis of RT_1 in the *transfer phase* involved the predictive (U-P) and the three unpredictive (P-U, U-U, M-U) conditions. The ANOVA only showed a significant main effect of blocks ($F(3,168)=3.43$, $p<0.01$). Despite the suggestive differences in mean RT_1 (Fig. 1) the effect of mode was not significant ($F(3,56)=2.13$, $p>0.10$), but there was a trend towards an interaction between mode of training and blocks ($F(9,168)=1.76$, $p<0.08$). Hence, analyses were performed on each mode separately showing main effects of blocks in the transfer phase in P-U ($F(3,42)=3.31$, $p<0.03$) and M-U ($F(3,42)=3.39$, $p<0.03$) but not in U-U ($F(3,42)=0.2$, $p>0.10$) and U-P ($F(3,42)=2.19$, $p>0.10$).

The comparison between RT_1 in the fourth single block and the succeeding dual block (block 13) showed a main effect of single/dual ($F(1,56)=107$, $p<0.01$) indicating that single RT_1 was still always faster. The second order interaction between the effects of single/dual and mode of training/transfer ($F(3,56)=5.18$, $p<0.01$) indicated again, that mode did not affect single RT_1.

The effect of transfer was directly addressed in an ANOVA on dual block 7 to 14 (transfer was between block 10 and 11) and training/transfer mode P-U, U-U, and U-P. The interaction between effects of mode of training/transfer and blocks ($F(14,294)=21.3$, $p<0.01$) indicated that P-U became slower and U-P faster as a result of transfer. This was confirmed by analyses on block 10 and 11 (P-U: $F(1,14)=32.3$, $p<0.01$; U-U: $F(1,14)=0.70$, $p>0.10$; U-P: $F(1,14)=41.5$, $p<0.01$).

Errors did not exceed three percent and analyses did not yield any interesting information other than that the observed differences in RT were not caused by speed-accuracy trade-off.

Effects on RT_2. Mean RT to S_2 is shown in Fig. 2 as a function of mode of training/transfer and training. The analysis of RT_2 in the *training phase* included P-U, U-U, and U-P and showed main effects of blocks ($F(9,378)=39.8$, $p<0.01$) and mode of training/transfer ($F(2,42)=42.6$, $p<0.01$). Since an ANOVA on U-U and U-P showed no significant effect of mode ($F<1$) and the mode effect in P-U differed from that in U-U ($F(1,28)=52.8$, $p<0.01$) as well as U-P ($F(1,28)=93$, $p<0.01$) the effect of mode can be clearly attributed to the difference between P-U on the one and U-U and U-P on the other hand.
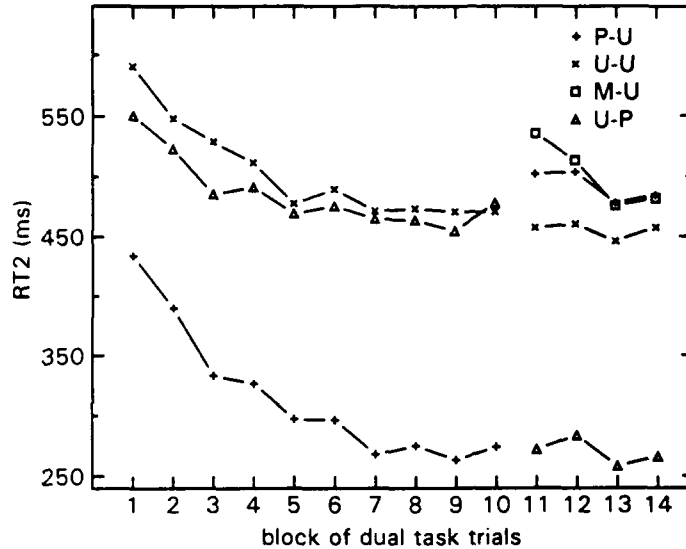
Fig. 2 RT₂ as a function of practice and mode of train-
ing and transfer.

An interaction between the effects of training/transfer mode and
blocks ($F(18,378)=1.66$, $p<0.05$) indicated that improvements in the
first blocks of P-U (see Fig. 2) were larger than in U-U and U-P. The
main effect of RSI ($F(4,168)=70.1$, $p<0.01$) indicated that RT₂ was
faster as RSI was longer (Fig. 4). An interaction was found between
the effects of training/transfer mode and RSI ($F(8,168)=3.6$, $p<0.01$)
which showed that P-U was more sensitive to RSI than U-U and U-P. In
P-U RT₂ was almost 70 ms slower at RSI 100 than at RSI 1200 whereas for
U-U and U-P this difference amounted to resp. 46 and 36 ms. Finally,
an interaction between blocks and RSI ($F(36,1512)=1.67$, $p<0.01$) indi-
cated that, irrespective of predictability, practice reduced RT₂ at
short RSI values more than at long RSI values.

The *transfer phase* analysis on P-U, U-U, M-U, and U-P showed main
effects of mode ($F(3,56)=57.1$, $p<0.01$), blocks ($F(3,168)=17.4$, $p<0.01$)
and RSI ($F(4,224)=69.0$, $p<0.01$). Pair-wise comparisons showed signifi-
cant differences between U-P and M-U ($F(1,28)=371$, $p<0.01$), U-P and
P-U ($F(1,28)=210$, $p<0.01$), and U-P and U-U ($F(1,28)=65.5$, $p<0.01$) but
not between P-U and U-U ($F(1,28)=2.0$, $p>0.10$), M-U and U-U ($F(1,28)=
3.66$, $p=0.06$), and P-U and M-U ($F<1$). So, the main effect was due to
the difference between U-P on the one and P-U, U-U, and M-U on the
other side.

An interaction between the effects of mode of training/transfer and blocks ($F(9,168)=3.08$, $p<0.01$) indicated that there was no significant effect of blocks in mode U-U in contrast to P-U, U-P, and M-U. This was confirmed by separate analyses on these modes (effect of blocks in mode P-U $F(3,42)=2.99$, $p<0.05$; in U-U $F<1$; in M-U $F(3,42)=19.5$, $p<0.01$; in U-P $F(3,42)=5.15$, $p<0.01$).

The effects of the change from training to transfer phase were directly addressed in an analysis of dual block 10 to 11 in mode P-U, U-U, and U-P. It revealed a training/transfer mode x blocks interaction ($F(2,42)=368$, $p<0.01$). Separate analyses on block 10 and 11 in each mode, indicated that, in contrast to U-U ($p>0.10$), mode P-U and U-P changed significantly (resp. $F(7,98)=19.4$, $F(7,98)=242$, both $p<0.01$) after transfer.

A final analysis on RT_2 concerned consistency which refers to S_1-S_2 pairs after transfer that were identical to those that had originally been trained. The ANOVA consisted of a 2 x 2 x 8 x 4 x 5 (consistency x S_2 modality x subject x blocks x RSI) hierarchical design with S_2 modality as between-subject and consistency, blocks and RSI as within-subject variables. There was one significant interaction that will be discussed in the section on modality effects.

Analyses of errors in R_2 showed that error rates were usually below five percent and correlated positively with RT which did not suggest speed-accuracy trade-off.

Analysis of the effects of consistency on errors in the transfer phase of P-U indicated that inconsistent responses were incorrect more often than consistent responses (4.0 vs 2.5 percent, $F(1,14)=17.6$, $p<0.01$). The mean difference in error rate between consistent and inconsistent responses were one percent for VA and two for VV in the transfer phase of P-U.

Finally, analyses of anticipatory responses in the predictive blocks (training of P-U and transfer of U-P) showed an effect of RSI (resp. $F(4,56)=13.5$, $p<0.01$, and $F(4,56)=25.4$, $p<0.01$) indicating that anticipatory responses were only emitted at longer RSI values. For RSI 800 and 1200 ms the percentages were about two percent in the training phase of P-U and five percent in the transfer phase of U-P. No significant effects were found of practice and modality. In the unpredictive conditions anticipatory responses were below one percent.

3.2   Effects of S_2 modality

Effects on RT_1. The ANOVA on P-U, U-U, and U-P in the training phase showed an S_2 modality x blocks interaction ($F(9,378)=6.82$, $p<0.01$). This indicated that in all training modes, improvements of RT_1 were larger when S_2 was visual (Fig. 3). This was confirmed in the analysis of the difference between single and dual performance by a single/dual x S_2 modality x blocks interaction ($F(2,84)=9.67$, $p<0.01$).
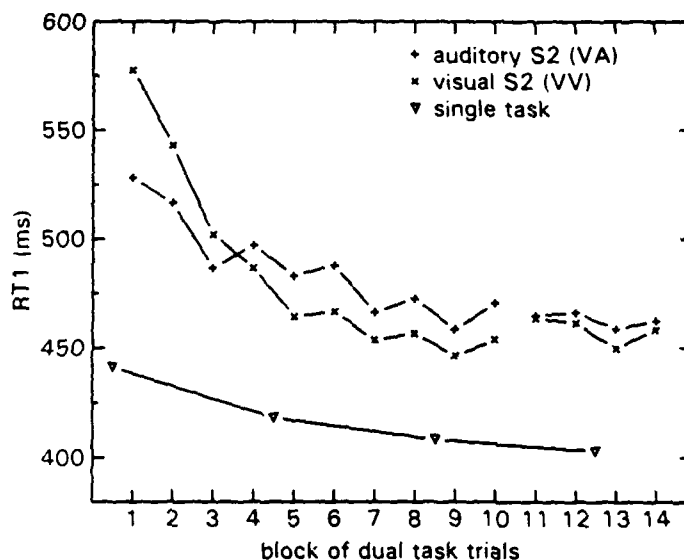
Fig. 3 RT_1 as a function of practice and modality of S_2.
VA is the condition with Visual S_1 and Auditory S_2, VV is the condition with Visual S_1 and S_2.

The ANOVA on RT_1 in block 10 and 11 showed an interaction between the effects of mode of training/transfer, modality and blocks ($F(2,42)=4.34$, $p<0.02$). Separate analyses per mode of training/transfer on block 10 and 11 showed that after transfer RT_1 decreased more in P-U/VV than in P-U/VA as indicated by the modality x blocks interaction (76 vs 25 ms, $F(1,14)=8.3$, $p<0.02$). In contrast, the analysis of U-P showed no interaction between modality and blocks (F<1).

Effects on RT_2. Auditory stimuli (S_2) gave faster responses which was indicated by the modality main effects in the training ($F(1,42)=9.8$, $p<0.01$) as well as in the transfer phase ($F(1,56)=17.9$, $p<0.01$) in

P-U, U-U, and U-P. The interaction between modality and blocks in training ($F(9,378)=2.6$, $p<0.01$) indicated that RT_2 decreased more with practice in the visual S_2 than in the auditory S_2 condition.

In the ANOVA on block 10 and 11 an interaction between mode of training/transfer, modality and blocks indicated different effects of transfer depending on modality and mode of training/transfer ($F(2,42)=5.72$, $p<0.01$). Subsequent ANOVAs on P-U, U-U, and U-P showed that in P-U/VV RT_2 dropped more than in P-U/VA (RT_2 increase was 264 vs 190 ms, $F(1,14)=7.84$, $p<0.02$) whereas in U-U and U-P, VV and VA did not differ ($p>0.10$).

The interactions between modality and RSI in the analyses on practice ($F(4,168)=14.9$, $p<0.01$, see Fig. 4), transfer ($F(4,224)=13.5$, $p<0.01$), and training to transfer (block 10 to 11, $F(4,168)=9.09$, $p<0.01$) all showed that responses to an auditory S_2 were more sensitive to RSI than responses to a visual S_2.
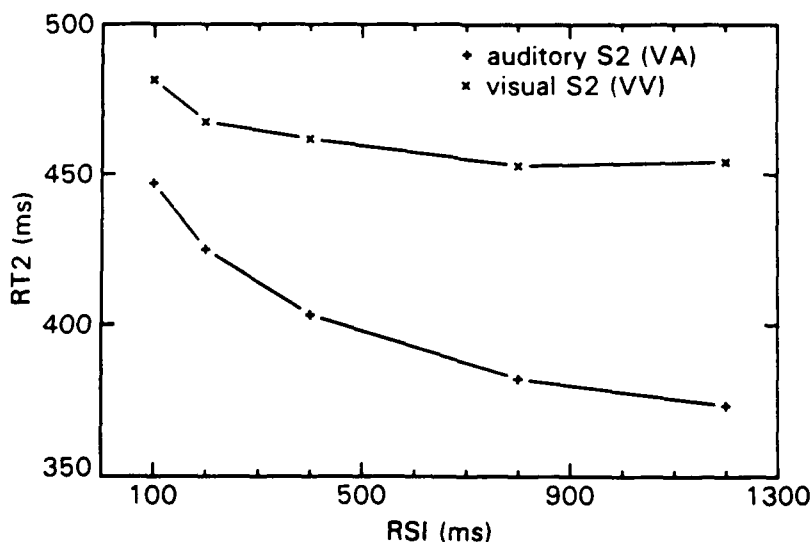

Fig. 4 RSI sensitivity of RT_2 as a function of S_2 modality in block 1 to 10.

The ANOVA on consistent versus inconsistent trials showed an interaction between modality, blocks and consistency ($F(3,42)=3.93$, $p<0.02$). Fig. 5 suggests a consistency effect for both modalities but separate

analyses of modality showed that only in VV there was a significant interaction between blocks and consistency ($\underline{F}(3,21)=5.7$, $\underline{p}<0.01$) indicating that consistency had only a significant effect in the first transfer blocks in the VV condition. In the ANOVA on errors in the transfer phase, a marginally significant interaction between modality, consistency and blocks ($\underline{F}(3,42)=2.24$, $\underline{p}<0.10$) indicated that more errors were made at inconsistent trials at the earlier blocks of transfer in VV.
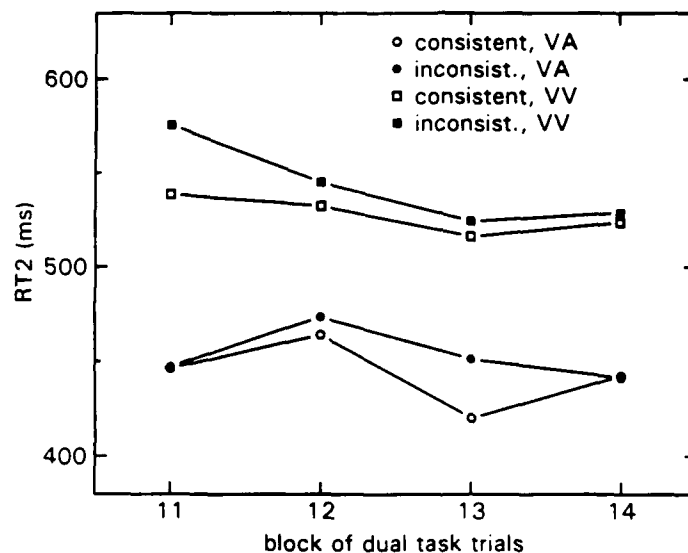
Fig. 5   RT$_2$ in the transfer phase of P-U as a function of practice and S$_2$ modality. Consistent stands for S$_2$-R$_2$ pairs that followed S$_1$-R$_1$ pairs as practiced during the training phase whereas inconsistent implies combinations of S$_1$-R$_1$ S$_2$-R$_2$ pairs which had not previously been trained.

3.3   Correlational analyses

Since large individual difference were observed, correlational analyses were performed in order to test post-hoc hypotheses as presented in the discussion. First, the correlation was calculated between, on the one hand, RT$_2$ in inconsistent minus RT$_2$ in consistent trials in the transfer phase (indicating the consistency effect) and, on the other hand, the difference between RT$_2$ at RSI 100 and RSI 1200 in block 5 to 10 in the training phase (indicator for overlapping preparation). This

correlation was highly significant and negative ($r=-.85$, $p<0.01$). Partial correlations showed that the relation was present in both modality groups (VA: $r=-0.80$, $p<0.02$, VV: $r=-.75$, $p<0.05$). RT_1 in dual block 5 to 10 and sensitivity of R_2 to RSI were not correlated ($r=0.007$). In addition, the correlation between RSI sensitivity of RT_2 and RT_2 at RSI 100 was strongly positive (VA: $r=0.84$, VV: $r=0.84$, both $p<0.01$) indicating that reduced RSI sensitivity was not caused by slower responding to S_2 when RSI was 100 ms. Finally, it was found in VV that subjects who had a relatively small difference between single and dual RT_1 were also less sensitive to RSI in block 5 to 10 ($r=0.84$, $p<0.02$) and showed a relatively large consistency effect ($r=-0.62$, $p<0.02$). In VA these correlations were insignificant.

4 DISCUSSION

This study aimed at testing predictions of three models about mechanisms underlying acquisition of successive responses. The voluntary control model does not expect the development of involuntary relations between successive responses. In contrast, the involuntary control model assumes that training a fixed stimulus-response pair promotes an integrated action pattern so that R_2 will be primed by S_1-R_1 beyond voluntary control. The hybrid model asserts that involuntary priming may develop at the perceptual level of information processing - either specific to the modality of stimulus presentation or not - but not at the central or motor levels.

A first main result was that, after transfer to an unpredictive mode, RT_2 did not appear to depend on the training mode (predictive, unpredictive, neutral). Second, RT_1 was longer in the predictive mode than in the unpredictive mode. Yet, in case of transfer the value of RT_1 immediately adapted to the new situation - either predictive or unpredictive - without evidence for after-effects due to the training mode. This independence of both RT_1 and RT_2 on prior practice argues strongly against the involuntary control model. Further evidence against the involuntary control model comes from the finding that RT_1 did not improve more when training a predictive relation (P-U) than an unpredictive relation (U-U, U-P). This result argues against the notion that priming develops during RT_1 so that gradually less attention is required for preparing R_2 during RT_1. Again no effect of consistent trails was observed after transfer suggesting that suppression of earlier practiced relations did not occur during RT_2. The absence of differences between RT_1 in M-U, P-U, and U-U after transfer argues

against the notion that suppression occurred during RT_1 in P-U. Final-ly, since RT_2 in the P-U transfer phase was not relatively slow at a short RSI, suppression did also not occur during RSI. Hence, all results argue against involuntary control.

Although an involuntary control model could not explain the present data, three findings suggest that it may be appropriate when more response alternatives are available, longer sequences (MacKay, 1982), or more similar responses are used. First, after transfer from P to U more errors were made on inconsistent than on consistent R_2s (4 vs 2.5 percent). Second, involuntary control is supported by a trend of a longer RT_1 after transfer at P-U than at U-U and M-U (Fig. 1), and, third, by a longer RT_2 at P-U than at U-U (Fig. 2). The last two effects were statistically insignificant but still suggest that a contribution of involuntary control for sequential actions deserves further scrutiny.

In order to decide between voluntary control and hybrid control con-sistency effects after transfer in P-U should be evaluated. Would information processing at modality specific levels of information processing be beyond voluntary control then transfer trials in VV, that are consistent with training, are expected to be *faster* than inconsistent trials. In VA this effect would be absent in case priming occurs at a modality dependent level. A consistency effect on RT_2 was found indeed in the first blocks of VV where there was also a trend towards more R_2 errors at inconsistent trials. Also, performance on both RT_1 and RT_2 decreased more when transferring to the unpredictive condition in VV than in VA while such a difference between VV and VA was not found when going from unpredictive training to predictive transfer (U-P). Thus, priming facilitated processing at the last blocks of the predictive training of VV (in P-U), but it did neither at the unpredictive transfer at VV nor at VA. Together, these findings argue in favor of the version of hybrid control which states that involuntary priming occurs only at a modality dependent level of processing.

Another prediction of the hybrid control model is that, since in the predictive condition attention demanding preparation at the perceptual level is gradually replaced by involuntary priming, RT_1 should improve more as a function of practice at VV than at VA. This was confirmed (Fig. 3), but in contrast to expectations it also occurred in the training phases of the unpredictive conditions U-U and U-P at VV. This argues against priming of specific stimulus representations. Post-hoc explanations are that priming was stimulus aspecific (e.g., of a

stimulus category) and that the effect was not due to priming but because switching attention between sensory modalities at VA occurred during RT_1 and did not require less time with practice. The present results do not allow a decision between these options.

Preparatory processes during RT_1 and RSI. The finding that single RT_1 is always faster than dual RT_1, indicates that a forthcoming reaction slows down an earlier reaction, which suggests attention demanding preparatory processing of S_2-R_2 during RT_1. This finding is in line with the finding of overlapping preparation of successive reactions at a fixed and brief interval (Verwey, 1990b), and it shows that preparation of R_2 during RT_1 also occurs when RSI is variable. In cases of time-uncertainty, subjects appear to adopt a strategy of preparing some intermediate interval duration (Gottsdanker, 1980). In agreement with Verwey (1990b), preparatory processes during the earlier reaction appear not to be specific for the second reaction. They occur with and without knowing which next reaction to expect.

The finding that dual RT_1 improved more during practice than single RT_1 indicates that preparation of R_2 could be more efficiently time-shared with processing S_1-R_1. The finding that in the training phase P-U was more sensitive to the duration of RSI than U-U and U-P shows that preparing a predicted R_2 continued during RSI. This is also indicated by the finding that anticipatory responses only occurred at longer RSIs (cf. similar findings by Meyer et al., 1984, 1985). Yet, in the unpredictive as well as in the predictive conditions, subjects became more efficient in preparing the second reaction as indicated by the result that in all training conditions RT_2 decreased more at short than at long RSI (see also Sudevan & Taylor, 1987). Possibly, some specific preparation may have occurred in the predictive conditions during RT_1 as suggested by the trend of a difference in RT_1 between predictive and unpredictive training blocks (Fig. 1). It seems reasonable that the preparing of a larger response set, as required at the unpredictive condition, takes more time and attention than preparing a smaller set.

RT_2 was found to be relatively sensitive to RSI in VA. Again, switching of attention may have played a role herein under the assumption that it occurred, at least in part, during RSI and does not require less time with practice. The last assumption is supported by the notion that humans have lots of experience in attention switching so additional practice does not cause further improvement (MacKay, 1982).

Individual differences and the development of priming. So far, the results are in reasonable agreement with the hybrid control model.

Additional characteristics of the hybrid control model can be derived from correlational analyses. The basic motive for these analyses was the observation of large individual differences in the size of the consistency effect contingent on the modality of S_2 and on sensitivity of RT_2 to RSI. For instance, subjects in VV showed a difference between RT_2 on consistent and inconsistent trials ranging from 10 to 65 ms. In VA, the consistency effect even ranged from -50 to 60 ms. There is evidence for large individual differences with respect to the extent of parallel processing in a successive response paradigm (Damos, Smist & Bittner, 1983). Therefore, a post-hoc hypothesis for the individual differences is that in the predictive condition some subjects established an S_2 representation simultaneously with processing R_1 (Pashler, 1984; Wilkinson, 1990). By contrast, other subjects postponed preparation of S_2-R_2 processing until R_1 had been completed. This difference could explain the individual differences in the size of the consistency effect: early establishment of the S_2 representation could activate S_1 and S_2 representations in rapid succession which, according to the coactivation strengthening hypothesis (Hebb, 1949; Schneider & Fisk, 1984), could induce the development of associations between the stimulus representations enabling priming effects. So, the growth of perceptual priming would depend on the degree of overlapping preparation.

This hypothesis was tested by calculating the correlation between the consistency effect and an indicator of overlapping preparation. If perceptual priming at the perceptual level is indeed the result of coactive stimulus representations then the consistency effect in the transfer phase of P-U should correlate with the degree of overlapping preparation during the practice phase. The difference between RT_2 at RSI 100 and RSI 1200 in block 5 to 10 of the training phase was taken as indicator for overlapping preparation, little sensitivity to RSI indicating overlapping preparation. The correlation between consistency in the transfer phase and overlapping preparation in the training phase was found to be highly negative and significant. This confirms that subjects who already prepared S_2-R_2 while encoding S_1 and, hence, prior to executing R_1 also developed perceptual priming. Partial correlations showed that the relation was present in both modality groups. RT_2 and error analysis have previously indicated that perceptual priming occurs at a modality dependent level. The partial correlations indicate that priming also occurs at a modality independent level. This is further supported by non-significant differences in RT_2 between consistent and inconsistent trials after transfer in P-U/VA (Fig. 5). Yet, priming at modality-independent levels of information processing as occurred in VA appears to have been less powerful than the total of modality-dependent and independent priming in VV.

It could be argued that sensitivity of RT_2 to RSI does not reflect overlapping preparation, but, instead, complete absence of preparing prior to presentation of S_2. Yet, this can be rejected since RT_1 in the dual blocks 5 to 10 and RSI sensitivity were uncorrelated. If some subjects would not have been sensitive to RSI on RT_2 because they did not prepare RT_2 at all, this correlation should have been highly positive. The point is that, in the absence of preparatory activity for R_2, RT_1 should have been much faster and comparable to single RT_1. In addition, the correlation between sensitivity of RT_2 for RSI and RT_2 at RSI 100 was strongly positive indicating that reduced RSI sensitivity was not due to responding slower to S_2. This only further supports the notion that reduced RSI sensitivity of RT_2 is indeed due to overlapping preparation.

Finally, it was found at VV that subjects who had a relatively small difference between single and dual RT_1 were also less sensitive to RSI in block 5 to 10. These subjects also showed a relatively large consistency effect. By contrast, in VA these correlations were reversed and insignificant. This is further support for the earlier hypothesis that priming primarily develops in a modality dependent system since subjects who had overlapping preparation profited from priming at training and showed an advantage at consistent trials after training.

Together, the correlation analyses provide evidence for the coactivation hypothesis (Hebb, 1949; Schneider & Fisk, 1984) because the data suggest that priming develops only when the representation of S_2 are activated while the earlier stimulus representation is active as well. The result that there are also weak effects of consistent trials when successive stimuli are presented to different sensory modalities suggests th.t priming primarily occurs at a modality dependent level of information processing but that some priming develops at a modality independent level as well. This is consistent with the notion that attributes at several levels of information processing can be primed (e.g., Bajo & Canas, 1989; Nelson, 1979) and, furthermore, provides support for a multiple processor view of information processing (e.g., McLeod, 1977; Navon & Gopher, 1979; Wickens, 1984) that assumes that associations between representations can only occur within processing systems and not between systems. These notions have been elegantly modeled in the connectionist-control architecture as proposed by Schneider (1985; Schneider & Detweiler, 1987, 1988).

5   CONCLUSIONS AND IMPLICATIONS

The present study investigated mechanisms that underlie the acquisi-
tion of sequential skills. As discussed in the introduction, insight
in the nature of skill acquisition is badly required in order to build
a proper driver model used for the design of intelligent interfaces.
The results warrant several implications; implications for the devel-
opment of driver models, for interface design, and for future re-
search.

The present study showed that practice in a consistent environment has
different consequences for information processing at the perceptual
and motor level of information processing. Also, individual differ-
ences, possibly under strategical control, were found to have effects
on the development of integrated action patterns in the sense that
preparation during earlier actions correlated with the degree of
involuntary effect in the transfer condition. These findings indicate
basic properties of the human information processing system which
should be accounted for by any model of the human driver. The results
indicate that a connectionist-control architecture might be a good
candidate to model driver performance.

The finding that information processing at the perceptual level of
information processing is facilitated without explicit intention when
stimulation is in one sensory modality also bears some direct conse-
quences for the development of GIDS dialogues. Namely, it emphasizes
that stimuli to one integrated skill or subsystem in a complex car-
driver interface (Verwey, 1990b) should be presented in one sensory
modality. This facilitates integration of information processing in
sequentially performed actions and prevents the need for attention
switching which appears not to improve much with practice. At the
response level of information processing, voluntary control appears to
operate through preparatory processes that determine which responses
are preactivated. So, attentional demands and workload are reduced by
tuning the information processing system in advance according to
expectations. For GIDS systems, these results warrant the notion that
any interaction between the driver and the car interface should be
transparent and predictable since this allows preprogramming of
response sequences and the timely direction of attention. Also, when
an interface requires fixed response sequences (e.g. typing a tele-
phone number or going through a menu system), care should be taken
that such sequences do not interfere with less frequently used se-
quences which are only slightly different.

Lastly, the hybrid model of action control suggests some interesting research questions. A question of primary interest is whether priming of responses is fully excluded in favor of voluntary preparation. For example, MacKay's (1982) theory suggests that situations involving longer action sequences, more complex choice reactions, or full pre-dictivity in combination with short fixed RSIs may still yield invol-untary effects of response priming. Another question for further research is one of great theoretical importance. Resource theories assert that with practice resource demands are lessened (Lamberts & d'Ydewalle, 1990; McLeod, 1977; Wickens, 1984). So, when one assumes that overlapping preparation is enabled by reduced resource demands, overlapping preparation would be quite easily adaptable to new timing constraints. For example a slight increase in RSI would not slow down RT_1, and might even reduce RT_1, because preparation is allowed to be less overlapping. On the other hand, models that assume that simulta-neous processing at several levels of information processing is possi-ble because of the emergence of an attention-switching scheme (Broadbent, 1982) predict that RT_1 will be slowed by the same amount of RSI lengthening because the attention switching scheme is no longer efficient. These and other issues surely require further investigation in order to come to versatile models of human information processing in general and driver models in particular.

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

This report argues that in order to develop reliable intelligent interfaces in motor cars, a driver model should be developed which reflects human information processing mechanisms and, more specifically, mechanisms of skill acquisition. Two mechanisms are proposed to underlie skill acquisition, namely involuntary priming and voluntary preparation. On this basis three alternative models of skill acquisition are proposed that differ with respect to the effects of voluntary control at the perceptual and response level of information processing. Subjects carried out two-choice reactions in rapid succession. The most important experimental manipulations were (1) whether the first choice reaction predicted the second and (2) the degree of transfer of training to conditions where predictivity changed. In addition, stimulus presentation was for some subjects always visual whereas for other subjects only the first stimulus was visual and the second was auditory. The results support a model asserting that involuntary effects of priming evolve only at the perceptual level but not at the response level. In addition, they support earlier findings that preparation for the second reaction occurs, in part, before execution of the first one. Correlational analyses of individual differences indicate that an overlapping strategy during training yields involuntary priming whereas a sequential strategy without overlapping preparation does not. Together, the results are in close agreement with a connectionist-control model of human information processing which consists of separate processing modules each of which can be described as a neural network (Schneider & Detweiler, 1987, 1988). Finally, implications for the Generic Intelligent Driver Support (GIDS) system are presented.

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